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Einstein X-ray Observations of Cataclysmic Variables

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ABSTRACT

Observations with the imaging X-ray detectors on the Einstein Observatory have led to a large increase in the number of low luminosity X-ray sources known to be associated with cataclysmic variable stars(CVs). The high sensitivity of the Einstein instrumentation has permitted study of their short timescale variability and spectra. The data are adding significantly to our knowledge of the accretion process in cataclysmic variables and forcing some revision in our ideas concerning the origin of the optical variability in these stars.

INTRODUCTION

Before the launch of the Einstein Observatory, X-ray emission had been detected from only a small fraction of the total number of known cataclysmic binaries. Very strong ultra-soft X-rays (kT~20-40 eV) had been observed from some of the magnetic (AM Her) variables and also from two dwarf novae, SS Cyg and U Gem, during their outburst state [1,2,3,4,5,6]. In addition a very soft transient source observed with HEAO-1 [7] may be the cataclysmic variable, AC Cnc [8]. A weaker hard X-ray emission component (kT~10 keV) had also been detected from many of these same stars [9,10] and from a handful of others (e.g. EX Hya [11]). A survey of cataclysmic variables with the highly sensitive Einstein detectors has now demonstrated that weak hard X-ray emission is in fact a common property of these stars [12,13,14,15]. About 70% of the more than 50 cataclysmic variables surveyed with Einstein have been detected in the 0.1-4.5 keV band at a sensitivity level of $10^{29}(d/100pc)^2$ erg s^{-1}, including stars from each of the main CV sub-types. With the exception of the magnetic variables, however, no further examples of ultra-soft X-ray emission have been found.

THE SPECTRUM

The spectra of the X-ray brightest CVs (i.e. $f_x \sim 10^{-10}$ erg cm^{-2} s^{-1}) have been measured with the Einstein Objective Grating Spectrometer (OGS) and the Solid State Spectrometer (SSS). The OGS data on AM Her reveals that the ultra-soft X-ray component is continuous with no line emission [16], and is therefore consistent with a blackbody model as predicted by theoretical studies of accreting magnetic stars [17,18]. The hard X-ray spectrum of SS Cyg has been measured at various stages in its outburst cycle [19]. Two spectral components are required to fit the data. The cooler can be represented by a thermal bremsstrahlung model with a temperature of ~0.6 keV and does not change in temperature or strength during the optical outburst. During quiescence this component contains approximately 1/6 the X-ray luminosity above 0.4 keV. The second, hotter emission spectrum has a characteristic temperature of ~8 keV during optical quiescence, and ~5 keV during the outburst. An X-ray flare has been observed at the beginning and the end of the outburst in whch the spectral temperature rises to ~20 keV. A two component hard X-ray spectrum has also been found in EX Hya during quiescence (temperatures of 0.6 keV and ~5 keV; [19]).

Most CVs are not bright enough at X-ray wavelengths to detect with the SSS; instead the only existing spectral data on these stars comes from Einstein IPC. In some cases the Einstein MPC data is also of use. We have fit the IPC data (and MPC data when possible) of a number of CVs with a single temperature model to derive spectral parameters. These are listed in Table 1. We deduce from these fits that the dominant component observed in most CVs is relatively hard compared to the ultrasoft emission seen in the AM Her stars and U Gem and SS Cyg during outburst. The brightest stars in our sample, SU UMa and TT Ari, whose spectral parameters are the most tightly constrained, have best fit temperatures of about 10 keV.

TABLE 1 Spectral Parameters for CVs

Object	Optical State	Detector(s)	$N_H(cm^{-2})$	kT^* (keV)
TT Ari	high	IPC,MPC	$\sim 3 \times 10^{21}$	10
SU UMa	low	IPC,MPC	$\sim 8 \times 10^{20}$	8
GK Per	low	IPC,MPC	$\sim 5 \times 10^{21}$	0.6^+
U Gem	low	IPC	$<6 \times 10^{20}$	>0.4
HT Cas	low	IPC	$>2 \times 10^{21}$	---
V3885 Sgr	high	IPC	$<8 \times 10^{20}$	>0.5
BV Cen	low	IPC	$>5 \times 10^{20}$	---
TW Vir	low	IPC	$<1 \times 10^{22}$	>0.7
RW Sex	high	IPC	$<2 \times 10^{22}$	>0.3
V436 Cen	low	IPC	$<8 \times 10^{21}$	>0.3

Footnotes: * Spectral models are thermal bremsstrahlung plus Gaunt factor, except for +GK Per in which a blackbody model is a significantly better fit. Dashes indicate that kT is not constrained.

X-RAY AND OPTICAL FLUX

Two extreme accretion geometries have been considered for producing both hard and soft X-radiation from deep in the potential well of the degenerate dwarf star in cataclysmic binaries. In stars where the accretion disk around the degenerate dwarf penetrates all the way to the stellar surface, X-radiation may be produced in a boundary layer between the disk and the star. Here the rapidly orbiting material of the inner disk is forced to dissipate its excess Keplerian energy in shocks [20] or by viscous heating [21] in order to match the rotation rate of the degenerate dwarf. Alternately, in systems in which the degenerate dwarf possesses a magnetic field that is strong enough to disrupt the disk (thought to be the situation in the AM Her stars), accreting material is channelled by the field lines and falls pseudo-radially onto the magnetic polar regions of the star. A strong stand-off shock formed above the pole heats the accretion flow to X-ray temperatures [17,18].

Both models predict a transition from hard X-ray to lower frequency radiation as the accretion rate increases. In the case of accretion in the presence of a magnetic field, relatively low frequency cyclotron radiation is expected to become increasingly important as a cooling mechanism when the density (accretion rate) increases; this occurs at the expense of hard bremsstrahlung photons [17,18]. In the case of boundary layer accretion, hard X-rays will be formed if the adiabatic expansion timescale of the gas heated in the boundary region is shorter than the time it takes it to cool by free-free emission. The hot gas can then form a hard X-ray emitting "corona" around the compact star [20,21]. At higher accretion rates free-free cooling becomes more efficient so that the gas cools before it can expand out of the disk. The boundary layer radiation is then absorbed and thermalised in the disk, yielding a much softer X-ray emission spectrum [22].

The Einstein data provide some support for an effect of this kind in that, among the disk accreting stars, the proportion of the total flux emitted as hard X-rays is found to be highest for objects with the lowest accretion rates. In Figure 1 we show the ratio of X-ray to V band flux as a number distribution for three categories of cataclysmic variable observed with Einstein: dwarf novae in quiescence, dwarf novae in outburst and the combined sample of classical novae, recurrent novae and nova-like objects. There is a distinct separation between the dwarf novae in quiescence, where the accretion rate is low, and the dwarf novae in outburst, where the accretion rate is high, with typical ratios of F_x/F_V being 1 and 0.06 respectively in the two cases. The distribution of F_x/F_V for the classical novae, recurrent novae and nova-like objects shows a comparatively large spread, reflecting the greater inhomogeneity of this grouping. However, most have $F_x/F_V < 0.1$, consistent with the expectation that these stars in general have relatively high accretion rates compared to dwarf novae in quiescence. The magnetic variables have not been included in Figure 1 because many of these stars have significant soft X-ray components which complicates the conversion from detected counts to F_x in the relatively poor spectral resolution data obtained with the IPC detector on Einstein. However, the best estimates suggest that the F_x/F_V ratio for these stars is generally at the high end of the distribution for dwarf novae in quiescence. This is to be expected since these stars probably do not possess a substantial optical and UV emitting disk, and is consistent with the fact that six of the nine such stars known at the present time have been identified through X-ray surveys -- four of them, E0139-681, E1013-477, E1114+182 and E1405-451, recently discovered using Einstein [23,24,25].

The distances to individual cataclysmic variables are on the whole poorly determined, which means that there is a corresponding uncertainty in their absolute luminosities. The mean distance of the most prominent dwarf novae is thought to be about 100 pc based on space density arguements [26]. Adopting this distance, the mean 0.1-4.0 keV X-ray luminosity of these stars is found to be 2×10^{31} erg s^{-1} (hard component only) in optical quiescence and 2×10^{30} in optical outburst.

The subclass of cataclysmic variable whose distances are the most accurately determined are the classical novae. The mean 0.1-4.0 keV luminosity of 13 classical novae whose X-ray fluxes have been measured using Einstein, and whose distances have been determined with reasonable accuracy, is between 5.6×10^{31} and 6.7×10^{31} erg s^{-1}, depending on whether the five stars in the sample that were not detected have zero flux or are present at the detection threshold.

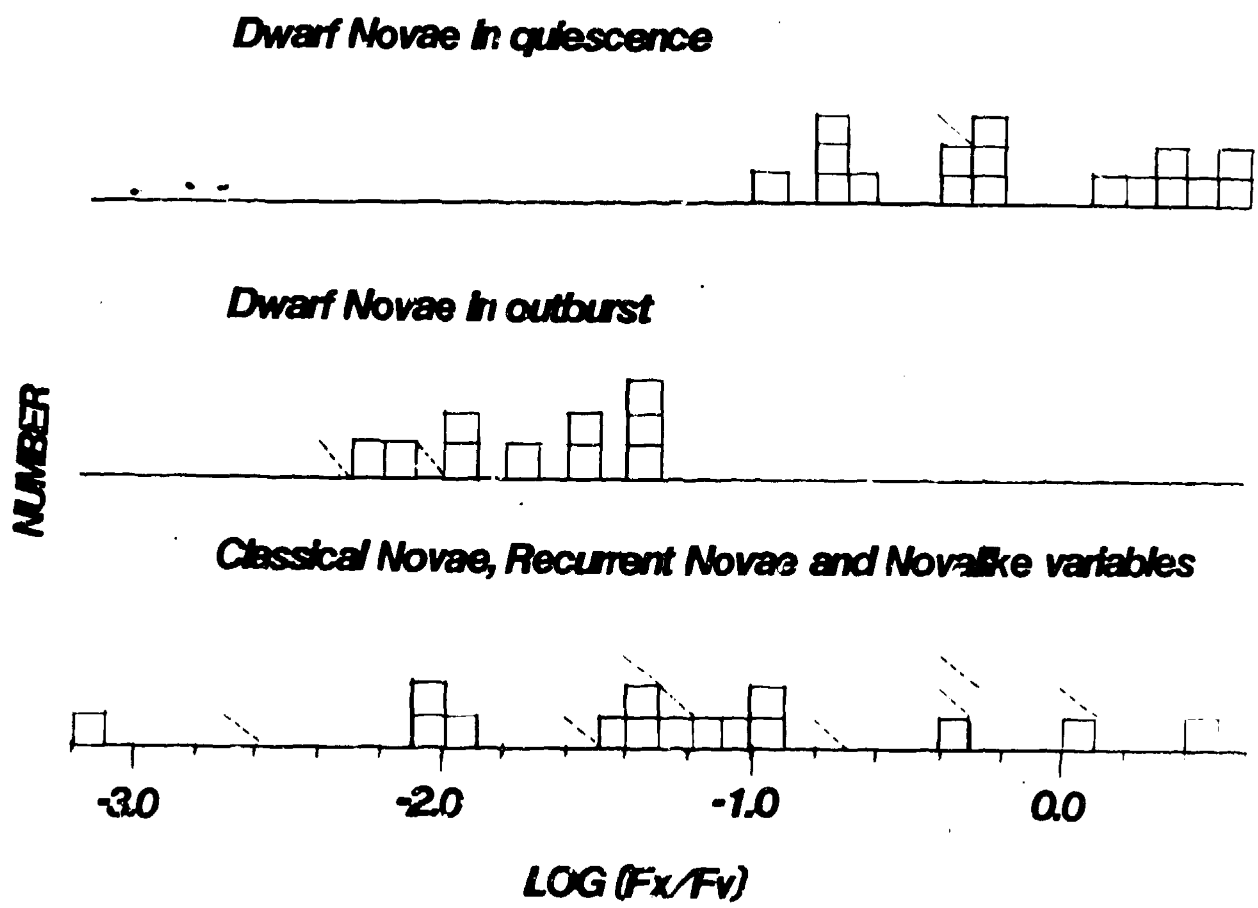

Fig. 1 Ratio of 0.1-4.0 keV flux to V band optical flux for various categories of cataclysmic variable plotted as a number distribution. Each square represents a star. The diagonal dashed lines represent X-ray upper limits.

This mean nova X-ray luminosity conflicts with the published value for the space density of these stars ($10^{-4}pc^{-3}$; [27]). Becker ([14]; see also [28]) calculates that the IPC should detect ~5 classical novae within 1 kpc in each 2000 s observation according to the above parameters, whereas the observed rate of accidental detection is less than 0.01. In contrast, the rate of accidental detection of dwarf novae is consistent with the space density given by Warner [26] of $5 \times 10^{-7}pc^{-3}$ [14,29]. There are a number of possible ways to resolve the nova discrepancy which bear further investigation: 1. There may be unrecognised selection effects that have biased the selection of nova targets for Einstein so that there is an unrepresentative mix of X-ray bright and X-ray faint classical nova in the sample. The mean X-ray luminosity of these stars could thus be lower than stated above. 2. The space density of novae may be overestimated. 3. There may be a transient increase in the X-ray emission from novae in the hundred or so years following the outburst. One possible source of such transient emission is the high velocity nova ejecta. However, Einstein HRI observations of the X-ray bright nova GK Per made by the authors failed to reveal any extended X-ray emission from the ~1 arc minute optical remnant of this star, making this explanation less tenable.

Becker and Marshall [13] have suggested that there is a relationship between the X-ray flux of classical novae at the present epoch and the rate of decline of the nova outburst in the optical band (speed class). Figure 2 is an updated version of the plot given by Becker and Marshall showing the X-ray luminosity of classical novae as a function of the rate of decline from the outburst. Figure 2 contains three stars in addition to those considered by Becker and Marshall, and revised data for a number of other stars based on information given by Webbink and Gallagher [30]. Complete references are given in Cordova and Mason [15].

Figure 2 illustrates that the brightest classical novae at X-ray wavelengths are indeed those with the fastest optical declines. However, CP Lac and particularly V1500 Cyg, both fast novae, do not appear to fit a simple linear relationship, while there is a large scatter also in the X-ray luminosity of the slow novae. The orbital inclination of the system may determine to some extent how much X-ray flux is observed because of obscuration by the disk. Two of the slow novae that were not detected as X-ray sources, DQ Her and T Aur, are probably

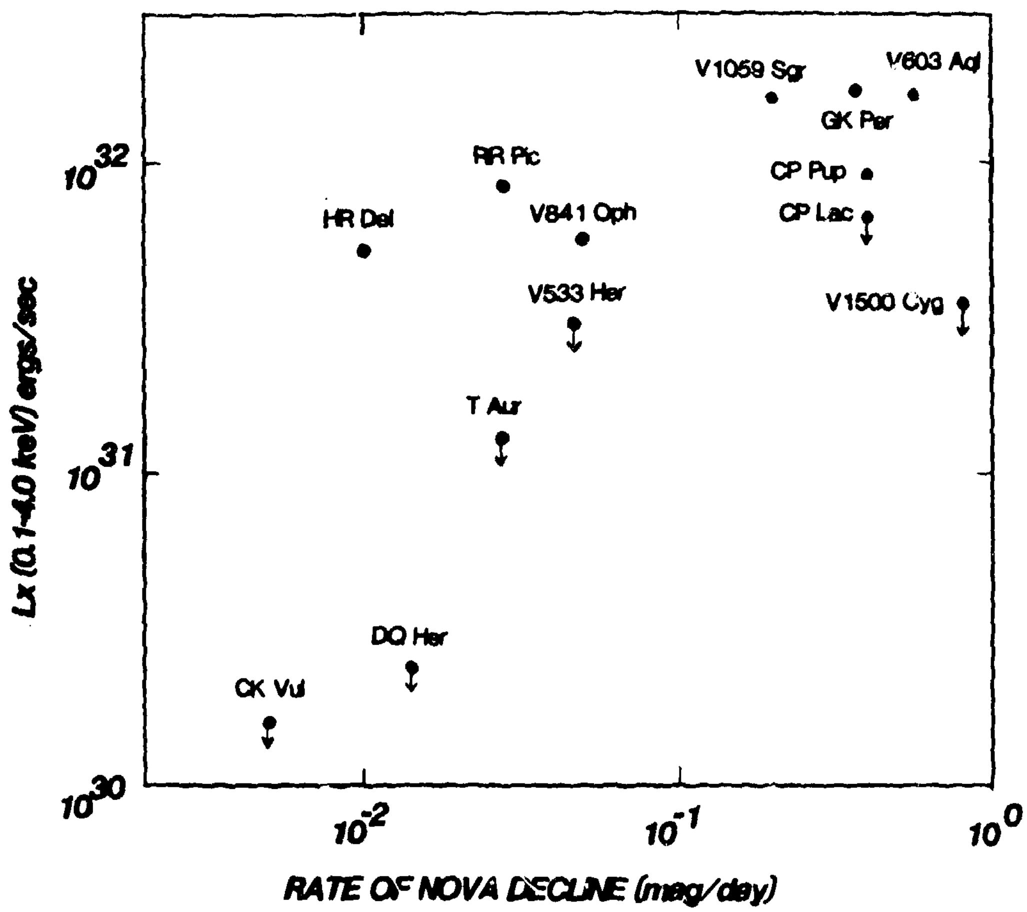

Fig 2 X-ray luminosity Vs rate of decline of nova outburst for classical novae.

high inclination systems, while the X-ray bright fast nova V603 Aql is probably a low inclination system. Clearly, further work is required to establish the reality of the suggested correlation between L_x and speed class.

OTHER SOURCES OF X-RAY EMISSION

There are a number of other ways in which X-ray emission might be produced by a cataclysmic variable. One, the nova remnant, has already been mentioned, but there are as yet no confirmed detections of extended X-ray emission around cataclysmic binaries. An earlier report of such a remnant around the dwarf nova SU UMa [31] is not confirmed in deeper IPC exposures of the star. The earlier detection may have been due to an unexplained instrumental effect or possibly the reflection off interstellar dust of very soft X-rays (similar to those observed from U Gem and SS Cyg) emitted during an outburst that preceeded the IPC observation [32].

Another possible source of X-ray emission is the corona of the companion (mass donating) star. The coronal X-ray emission of dwarf stars in non-interacting binary systems is found to scale inversely with their rotation period [33]. The relationship found for stars with rotation periods in the range 12 hours to tens of days, when extended to the shorter rotation periods expected for the companion stars in cataclysmic binaries (which are assumed to be phase locked to the binary period) suggests that coronal X-ray emission may be a significant contributor to the quiescent X-ray flux of a number of the lowest luminosity CVs. However the case is far from proven since there is no guarantee that stars in interacting binaries behave in the same way as those in non-interacting systems. Perhaps the best way to test whether the companion is a significant emitter is to observe systems in which the white dwarf is eclipsed by that star and to search for residual X-ray flux during the minimum.

One further possibility is that hard X-rays are produced in hot gas above and below the accretion disk. The detailed physics of how such a "corona" might be produced around the gas pressure dominated disk of a cataclysmic variable has not been worked out, but it is possible that vertical energy transport by acoustic or magneto-hydrodynamic waves could be efficient enough to excite such a corona [34,35,36]. There is evidence from the detection of P Cygni lines in the UV spectrum of some CVs [37,38] that vertical energy transport does occur in these stars, although it is not clear that this is necessarily related to the hard X-ray flux. We shall return to this question later in our discussion of the Einstein data on the novalike variable TT Ari.

TIME VARIABILITY

U Gem ultra-soft X-rays. Observations made with the HEAO-1 satellite revealed quasi-periodic oscillations in the soft X-ray flux of the dwarf novae SS Cyg and U Gem during optical outburst [39,40] with characteristic oscillation periods of ~9 seconds and ~25 seconds respectively. U Gem has twice been observed in outburst with Einstein, on April 2nd. 1979 with the HRI detector, and on October 12th. 1980 with the IPC detector [41]. On neither occasion was there clear evidence for a quasi-periodicity, although the X-ray flux was found to be variable on a timescale of 20 seconds. Figure 3a shows part of the HRI observation of U Gem plotted in 2 second integrations illustrating a ~15 second burst of radiation in which the count rate increased by as much as a factor of three. Figure 3b is part of the IPC observation of the star plotted in 10 second intervals. Again, variability on a ~20 second timescale is evident, particularly towards the end of the interval shown. There is clearly also variability by a factor of three on a timescale of about 1000 seconds, consistent with the factor of 10 or more variability observed earlier in scanning data obtained with HEAO-1 [6]. This long term variability was not detected in the HEAO-1 pointed observations.

EX Hya. This cataclysmic variable is unique in many respects. Optical spectroscopic and photometric observations of the star show that it is an eclipsing system with an orbital period of 98.26 minutes. Vogt, Krzeminski and Sterken [42] have recently identified an additional 67 minute photometric modulation in the optical band that has been stable for about 14 years. Kruszewski et al. [43] have observed EX Hya, one of the brightest CVs at X-ray wavelengths, with the IPC and HRI detectors on Einstein. They find that the X-ray flux is

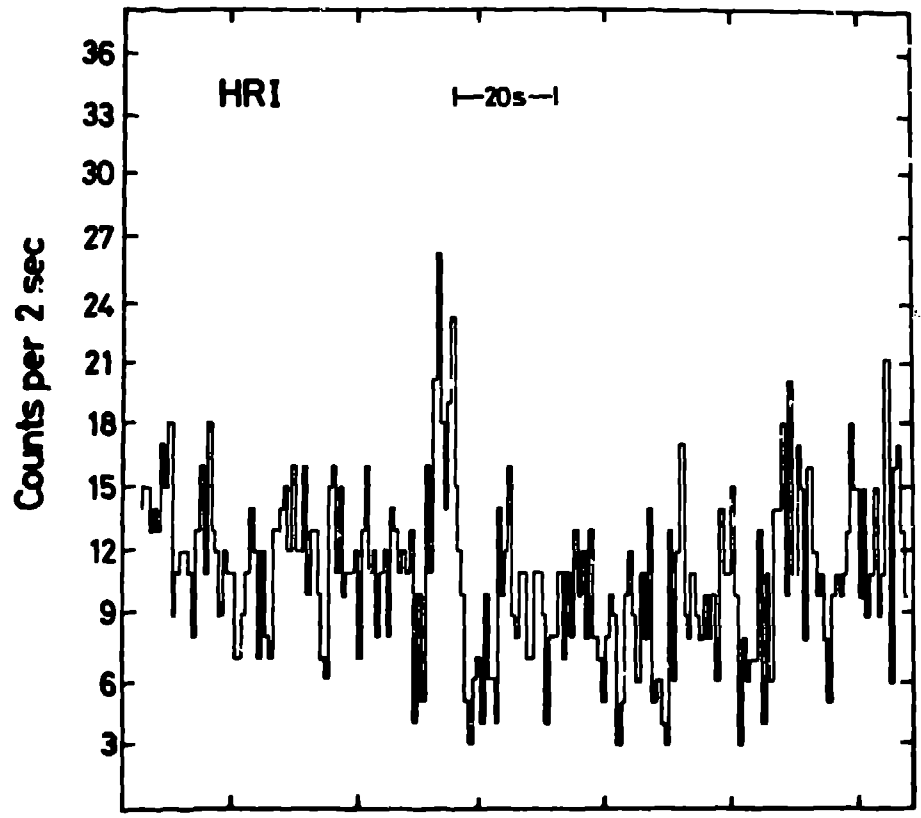

Fig. 3a Data from part of an HRI observation of U Geminorum made on April $2^{nd.}$ 1979. The integration time is 2 seconds.

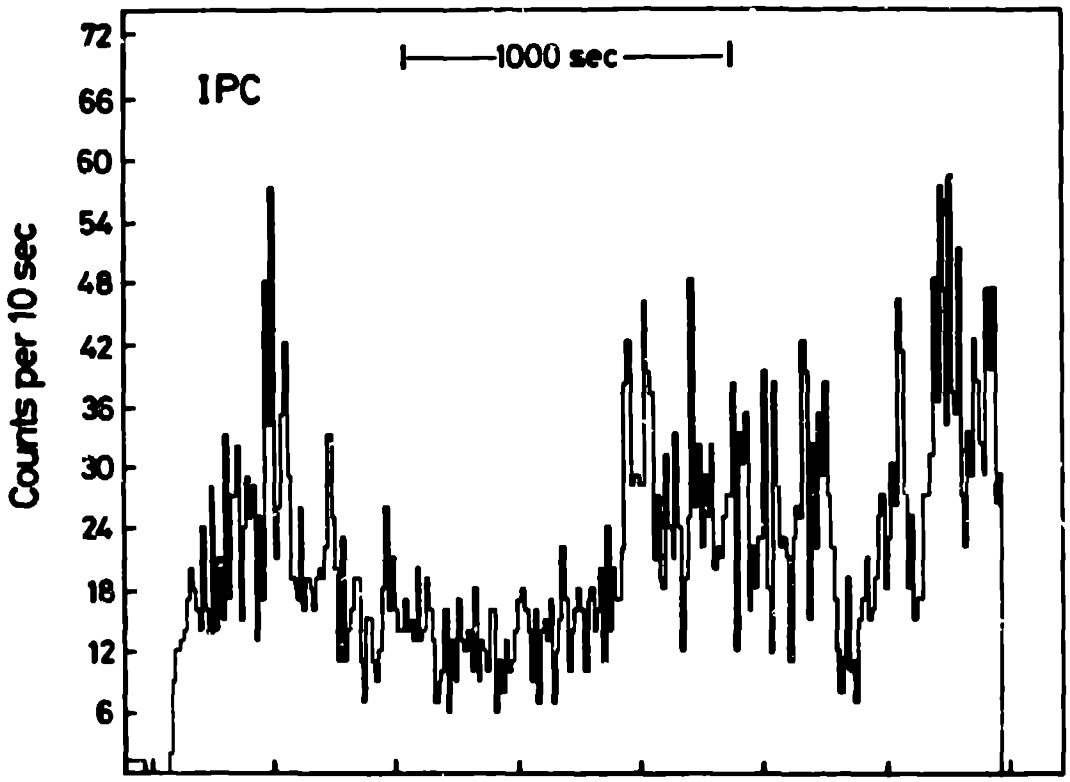

Fig.3b Data from part of an IPC observation of U Geminorum made on October 12th. 1980. The integration time is 10 seconds.

also modulated with the 67 minute period in the lowest energy channels of the IPC detector. The spectral data on the star are interpreted in terms of two components with temperatures of $kT > 3$ keV and $kT < 1.8$ keV respectively. Only the lower temperature component is modulated. The exact nature of the 67 minute period in EX Hya is debated. One suggestion is that the modulation is the rotation period of a magnetized white dwarf, and that this system is intermediate between the phase-locked AM Her stars and the rapidly rotating systems such as DQ Her [43,44]. An alternate suggestion is that variable mass transfer modulates the emission of a bright spot [42,45,44]. The observation that the X-ray flux is modulated with the same period as the optical light however, eliminates a model [44] in which the white dwarf rotates with a 40 minute period and the 67 minute optical modulation is caused by reprocessing of the beamed X-ray flux in material that is orbiting the white dwarf with the binary period.

Other Systems: Eclipses, Pulsations and Flickering. One of the potentially most powerful diagnostics the source of the X-ray emission in cataclysmic variable systems is data on eclipsing systems. An example is HT Cas which has an orbital period of 1.77 hours and an inclination of ~78°. This system has one of the highest ratios of F_X/F_V (~5) among the quiescent dwarf novae. We have observed HT Cas for about 2000 seconds with the IPC as part of an X-ray survey of CVs [46]. Part of the observation coincidentally included a time when the white dwarf was expected to undergo an eclipse by the companion star (the optical eclipse lasts about 5-6 minutes). During this time the X-ray flux dropped to a level consistent with detector background. The observation ended, however, before the expected time of eclipse egress. This result indicates that a substantial fraction of the X-ray flux emitted by HT Cas comes from the vicinity of the white dwarf.

Many of the CVs observed with Einstein exhibit variability in their X-ray flux on a timescale of a few hundred seconds [14,46]. Those which have been observed for extended periods (e.g. SU UMa and GK Per; [46]) and those observed more than once (e.g. MV Lyr; [14]) are also found to be variable on longer timescales. For instance both SU UMa and GK Per vary by a factor of two on timescales of ~1000 seconds.

Patterson [47] has reported the detection of X-ray pulsations in AE Aqr with the same period (33 seconds) as those seen in the optical band during a short IPC observation. A 2000 second observation of the dwarf nova YZ Cnc (probably in optical quiescence) obtained by the authors [46] also shows strong pulsations with a period of about 227 seconds. It would clearly be of interest to discover whether these pulsations are persistent.

<u>TT Ari</u>. The timescale for X-ray variability in the cataclysmic variables observed with Einstein is in many cases similar to that found in the optical. This suggests that simultaneous optical and X-ray measurements could be fruitful (although logistically difficult!). One such simultaneous observation was performed on the novalike variable TT Ari with interesting results. The star was observed with Einstein for four orbits on each of two successive days while simultaneous optical photometry was obtained from two ground based observatories, Louisiana State University and Mt. Wilson. The principle results of the observation [48] can be summarised as follows:

1. The X-ray flux is modulated with an amplitude of about 50% at a period that is consistent with the probable orbital period of the system (3.3 hours). No corresponding modulation of the spectrum is apparent. A similar modulation is found in the optical data, but the phase of the latter appears to lag behind the X-ray modulation by ~10% of the cycle.

2. There is strong flickering on a timescale of about 1000 seconds in both the X-ray and optical bands. The X-ray and optical flickering is highly correlated, but there is a time delay of about 60 seconds between the two bands such that the optical variability <u>preceeds</u> the X-ray variability. The fraction of the total light that is variable is significantly higher in the X-ray band than it is in the optical band.

3. Transient optical periodicities at ~12 seconds and ~32 seconds were detected during one 4000 second section of the optical data. The three highest peaks in the power spectrum of the simultaneous X-ray data occur at periods of 9 seconds, 12 seconds and 32 seconds. The probability that the 12 second and the 32 second peaks, corresponding to the optical

oscillations, are due to chance is 1.9 x 10^{-4} and 1.4 x 10^{-4} respectively. The pulsed fractions of the X-ray oscillations are ~15-25%, while the optical pulsed fractions are ~1.5-2%.

These data provide a wealth of clues as to the nature of TT Ari. Perhaps the most puzzling aspect of the data is the time delay between the optical and X-ray flickering. The possibility that this is due to an error in the calibration of the Einstein clock is remote [49] whereas the optical observations were made from two independent observatories whose data overlap and are consistent with one another. The 60 second delay appears to be too long for a reprocessing timescale. It may instead reflect the timescale for mechanical energy transfer within the system. One possibility discussed by Jensen et al. [48] is that TT Ari is related to the polar systems. In this model there is a partial disk around the white dwarf which is dirupted by the magnetic field of that star. The 60 second delay would be identified with the free-fall timescale from the point where the disk is disrupted (the site of the optical flickering caused by clumpiness in the accretion flow) to the surface of the white dwarf where the X-rays are formed. A second possibility is that the X-ray flux is generated in a low density coronal region above and below the disk. Oscillations in the disk might then drive pulses of energy away from the disk plane. These waves propagate into a less dense medium and are amplified, dissipating their energy in coronal shocks. The 60 second time delay is consistent with the acoustic travel time from the disk to the corona.

In any case, the observations of TT Ari demonstrate that the optical and X-ray flickering in this star are closely related. The ubiquitous flickering in CVs has traditionally been associated with the mass transfer bright spot on the outer part of the disk, although the evidence for this is derived from observations of only a few stars (e.g. U Gem). However, the bright spot is an unlikely site for the production of substantial hard X-ray emission. The observation that the hard X-rays in many systems also flicker, and the high degree of correlation between the X-ray and optical flickering in TT Ari, raises the possibility that the source of this variability in many CVs is to be found elsewhere in the system.

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